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This is a final report on the principal activities in Ocean Storms and Gulf of Cadiz observations as funded under ONR Grant "Oceanic Variability and Dynamics." Publications have appeared and are summarized in Table 1. Other projects were completed on the data sets from the Ocean Storms Experiment. The principal results of the Ocean Storms research are the development of the new profiler, the observation of spatially variable inertial motions and the determination of mean vertical shear. The three elements of the Gulf of Cadiz Expedition--Ampere Seamount Studies, Meddy Studies and Med Outflow Studies--have been successful, and are described in the publications referenced in Table 1.

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2. Please contact me if you require additional information. My e-mail is *silverr@onr.navy.mil* and my phone is (206) 625-3196.

ROBERT J. SILVERMAN

Final Report, Oceanic Variability and Dynamics
N00014-90-J-1100, 10/1/90 - 9/30/94
Thomas B. Sanford, Principal Investigator

Introduction

This is a final report on our principal activities in Ocean Storms and Gulf of Cadiz observations. Publications have appeared, such as the feature article in *Science* (Price *et al.*, 1993). Each of the three elements of our Cadiz expedition has been successful. Mark Prater defended his Ph.D. dissertation and has prepared two papers on the structure and dynamics of the Meddy we observed off Cape St. Vincent. Eric Kunze completed the analysis of small-scale vorticity around the Ampere Seamount. (Not unrelated is the fact that Eric received a Macelwane Award from the AGU as a young scientist who has already made significant contributions. His invited Sverdrup Lecture featured results from the Ampere Seamount studies.) Finally, Greg Johnson took the lead on the organization and submission of several papers on the results from the Med Outflow portion of the Expedition.

Other projects were completed on the data sets from the Ocean Storms Experiment and on a few XCP profiles in the Faroe Bank Channel.

Table 1 summarizes the publications which have resulted from these programs. The summary is categorized according to research project.

Ocean Storms

Our contribution to this experiment is described in Sanford *et al.* (1993) and consists of high resolution observations of the surface mixed layer (SML) temperature and velocity. We developed a new slow-fall AXCP (air-deployed expendable current profiler) for this work. The new profiler fell slowly through the SML so that surface wave contributions could be filtered from the velocity profile. This scheme allowed estimation of the low-frequency vertical shear in the SML.

The principal results of this research are the development of the new profiler, the observation of spatially variable inertial motions and the determination of mean vertical shear. The profiler and inertial motions were described in our last proposal. The determination and modeling of the mean vertical shear has been the focus of recent work and will be described here.

It was determined that the observed inertial motions were generally too large for the assumed wind stress. Second, substantial mean vertical shear was observed, contrary to some SML models. It was thought that perhaps the vertical shear might provide a clue about the true wind stress. To pursue this theory, a version of the Mellor-Yamada SML numerical model was applied to the parameterized Ocean Storms winds at our profiler sites. The numerical model results indicated the observed vertical shear was consistent with higher than assumed wind stresses. The interpretation is that the higher wind stress arises from higher drag coefficients caused by the very rough sea surface.

Table 1: Publications supported under this project

Gulf of Cadiz: Ampere Seamount Studies

Kunze, E. and T. B. Sanford, 1993: Submesoscale Dynamics near a Seamount: I. Measurements of Ertel vorticity. *J. Phys. Oceanogr.* **23,** 2567-2588.

Kunze, E., 1993: Submesoscale Dynamics near a Seamount: II. The partition of energy between internal waves and geostrophy. *J. Phys. Oceanogr.* **23,** 2589-2601.

Gulf of Cadiz: Meddy Studies

Prater, M. D. and T. B. Sanford, 1994: A Meddy off Cape St. Vincent, Portugal: I. Description. *J. Phys. Oceanogr.* **24,** 1572-1586.

Prater, M. D., 1994: A Meddy off Cape St. Vincent, Portugal: II. Origin and Generation. *J. Phys. Oceanogr.*, **24,** (in preparation).

Gulf of Cadiz: Med Outflow Studies

Johnson, G. C., T. B. Sanford, and M. O. Baringer, 1994b: Stress on the Mediterranean outflow plume: Part 1. Velocity and water property measurements. *J. Phys. Oceanogr.*, **24,** 2072-2083.

Johnson, G. C., R. G. Lueck, and T. B. Sanford, 1994a: Stress on the Mediterranean outflow plume: Part 2. Turbulent dissipation and shear measurements. *J. Phys. Oceanogr.* **24,** 2084-2092.

Other outflow studies:

Johnson, G. C. and D. R. Ohlsen, 1994: Frictional rotating channel exchange and ocean outflows. *J. Phys. Oceanogr.* **24,** 66-78.

Other studies:

Price, J.F., T.B. Sanford and G.Z. Forristall, 1993: Observations and simulations of the forced stage response to moving hurricanes. *J. Phys. Oceanogr.* **24,** 233-260.

Sanford, T.B., M.S. Horgan and N.A. Bond, 1994: Upper ocean velocities and shears in response to extreme winds. *J. Phys. Oceanogr.* (in preparation).

Sanford, T.B., J.A. Carlson, and M.D. Prater, 1995: An Electromagnetic Vorticity Meter. *APL-UW TR 9503,* Applied Physics Laboratory, University of Washington, Seattle, WA. 129 pp.

Gulf of Cadiz Expedition

The Expedition was sponsored by ONR and was conducted under the direction of four Principal Investigators: Tom Sanford and Eric Kunze of the University of Washington, Jim Price of the Woods Hole Oceanographic Institution, and Rolf Lueck of the University of Victoria. Oceanographers from Spain and Portugal also participated in the expedition. The objectives of the expedition were three-fold: to observe the vortices shed in the wake of Ampere Seamount, to survey eddies formed by the Mediterranean outflow (meddies) near Cape St. Vincent, Portugal, and to study the structure and dynamics of the outflow plume west of the Strait of Gibraltar. The most recent report on activities is the report of our Lisbon workshop in October 1991 (Ambar *et al.*, 1992). Since then many manuscripts have been submitted and several have appeared, particularly the *Science* article of Price *et al.* (1993). Each of the studies will be discussed next.

Ampere Seamount Studies

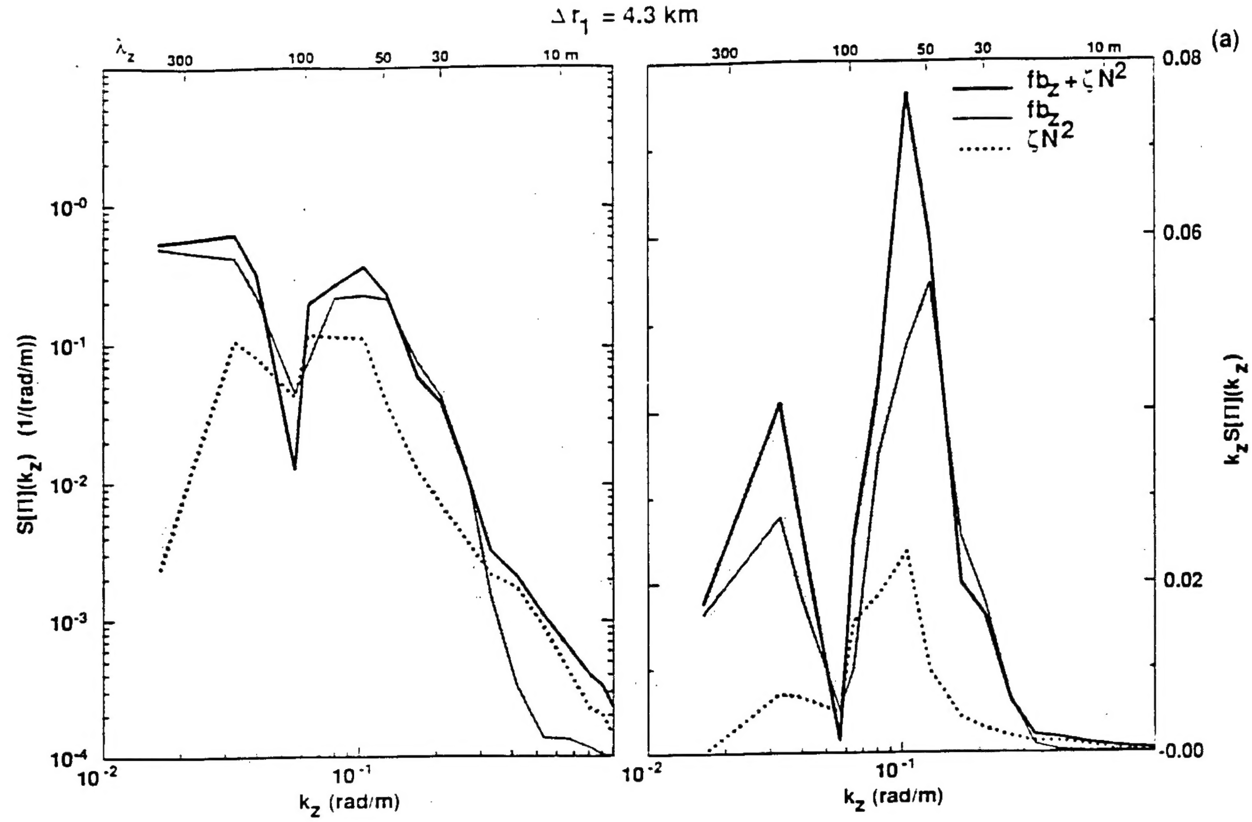
The Ampere Seamount component of the Gulf of Cadiz Expedition was designed to test the prevalent view that oceanic finestructure is dominated by internal waves. The test was framed in terms of observations of Ertel potential vorticity. Unlike geostrophic and nonlinear Ertel-vorticity-carrying motions, internal waves do not have Ertel vorticity fluctuations associated with them. By conducting coherent profile surveys, we are able to estimate the horizontal and vertical gradients that make up the Ertel vorticity(Π), where

$$\Pi = fN^2 + fb_z + (v_x - u_y)N^2 + (v_x - u_y)b_z + b_y u_z - b_x v_z \,,$$

including the nonlinear twisting terms. Ertel vorticity finestructure was found. Just as on basin scales, it is dominated by the stretching term fb_z. Two velocity and temperature profile surveys ~10 *km* in diameter collected beside Ampere Bank, revealed appreciable Ertel vorticity variance (Fig. 1) and thus a significant non-internal-wave component on horizontal wavelengths of 5-15 *km* and vertical wavelengths of 50-400 *m*. The anomalies are in geostrophic balance: the twisting terms, $b_x v_z$ and $b_y u_z$, are negligible, and the relative vorticities are less than $0.2f$. The interpretation that internal waves and geostrophic currents coexist on these scales is substantiated by comparison of the observed relationship between the energy ratio *PE/KE* and lengthscale ratio $(N\lambda_z/f\lambda_H)^2$ with the theoretical relations for internal waves and geostrophy.

It is unlikely that the anomalies arise from stirring of the largescale isopycnal gradients of stretching and planetary Ertel vorticity components because this would require stirring lengths of thousands of kilometers. The most likely source appears to be forcing at the seamount. However, generation by dissipative 3-D turbulence in the pycnocline or detrainment of the winter mixed-layer cannot be absolutely ruled out. It remains to determine whether coexistence of internal-wave and Ertel-vorticity-carrying fluctuations also characterizes motions on smaller scales ($\lambda_z < 50\ m$) and in waters away from the influence of topography.

Two papers have appeared in the *Journal of Physical Oceanography* on this work. "Submesoscale Dynamics near a Seamount: I. Measurements of Ertel Vorticity" by Eric Kunze and Thomas B. Sanford presents the Ertel vorticity



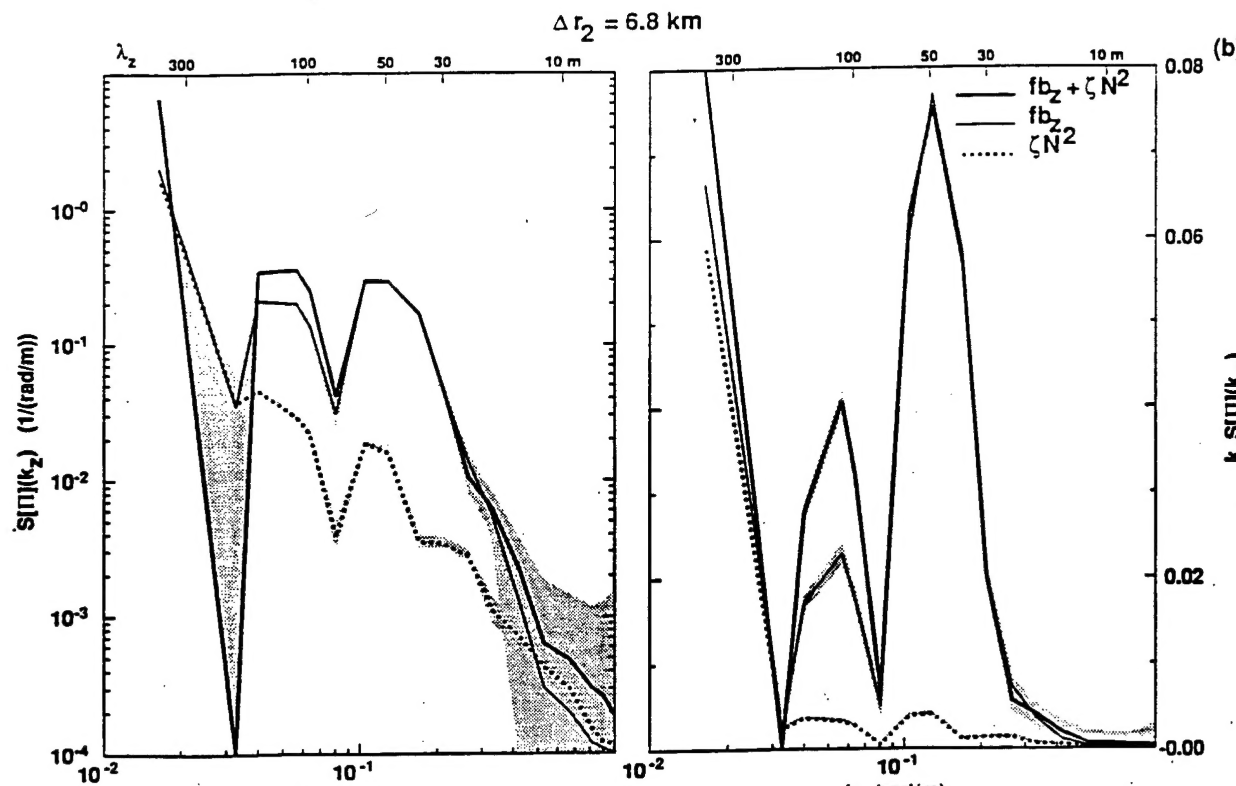


Figure 1: Vertical wavenumber spectra of the linear Ertel vorticity anomaly $fb_z + \zeta N^2$, vortex-stretching fb_z, and relative vorticity ζN^2 all normalized by fN_o^2 for the two surveys beside Ampere Seamount. The spectra are presented in loglog (left) and variance-preserving (right) forms. In both surveys, there is substantial Ertel vorticity variance on wavelengths $\lambda_z = 50$–$400m$ contributed mostly by vortex-stretching. For internal waves, vortex-stretching and relative vorticity would have equal but opposite magnitudes so that their sum, the Ertel vorticity anomaly would vanish. The Ertel vorticity anomaly in the spectral peaks exceeds vortex-stretching alone, indicating that the relative vorticity is in phase with the vortex-stretching. This is consistent with geostrophy.

analysis and general motivation. "Submesoscale Dynamics near a Seamount: II. The Partition of Energy Between Internal Waves and Geostrophy" by Eric Kunze focuses on using the theoretical relations between the energy ratio (or energy Burger number) and the lengthscale Burger number for internal waves and geostrophy to isolate the internal-wave and geostrophic contributions to finescale variance.

Meddy Studies

Characteristics of the Mediterranean outflow and of the Cadiz Meddy were used as criteria in evaluating models of Meddy generation. The lack of significant compression of isopycnals from the outflow to the Meddy along with a surplus of kinetic energy over available potential energy in the Meddy excluded pure geostrophic adjustment through vortex squashing as a primary generation mechanism. In addition, insufficient lateral shear existed in the outflow compared to the Meddy to support the hypothesis that the Meddy formed as the outflow separated from topography and barotropically closed upon itself. An alternate mechanism is suggested by the existence of a cyclonic partner (Fig. 2) with little of a Mediterranean water signature found east of the Meddy. The two eddies form a wave with a length on the order of 40 km, which is approximately twice the width of the outflow. This is consistent with an instability of the outflow.

The Ertel's potential vorticity (Q, defined similarly to Π earlier) was mapped across transects of the Mediterranean outflow using data from XCPs and CTDs. One transect was through the Cadiz Meddy formation region at Portimao Canyon south of Portugal (Fig. 3). The levels of Q in the outflow were similar to that found in the Meddy. However, the Q anomaly in the outflow was dominated by vortex stretching and vertical shear, while in the Meddy vortex stretching and lateral shear dominated. The transition between vertical and lateral shear is consistent with meanders within a geostrophic current in which anticyclonic curvature is introduced. A specific mechanism for the instability is not required, but is likely to come from a combination of baroclinicity and from curvature induced by variations in topography.

A thorough analysis of the Cadiz Meddy observations is presented in a paper "A Meddy off Cape St. Vincent Portugal: I. Description" by Mark Prater and Tom Sanford which was published in the *Journal of Physical Oceanography*. The unique temperature, density, and velocity structure of the Meddy was studied, along with an investigation of its potential vorticity anomaly. The energy content of the Meddy was computed, and the Cadiz Meddy was contrasted to other observed Meddies in a geometry-energy framework. A second paper by Mark Prater, "A Meddy off Cape St. Vincent Portugal: II. Origin and Generation" is in preparation. This paper focuses on using water properties on isopycnal surfaces to locate the Meddy formation site, and using characteristics of the Meddy and the Mediterranean outflow to determine probable Meddy generation mechanisms. The potential vorticity relationship between the Meddy and the outflow is an important constraint in this analysis.

Mark Prater, the former graduate student responsible for the Meddy component of the Cadiz Experiment, defended his dissertation titled "Observations and Hypothesized Generation of a Meddy in the Gulf of Cadiz" in April of 1992.

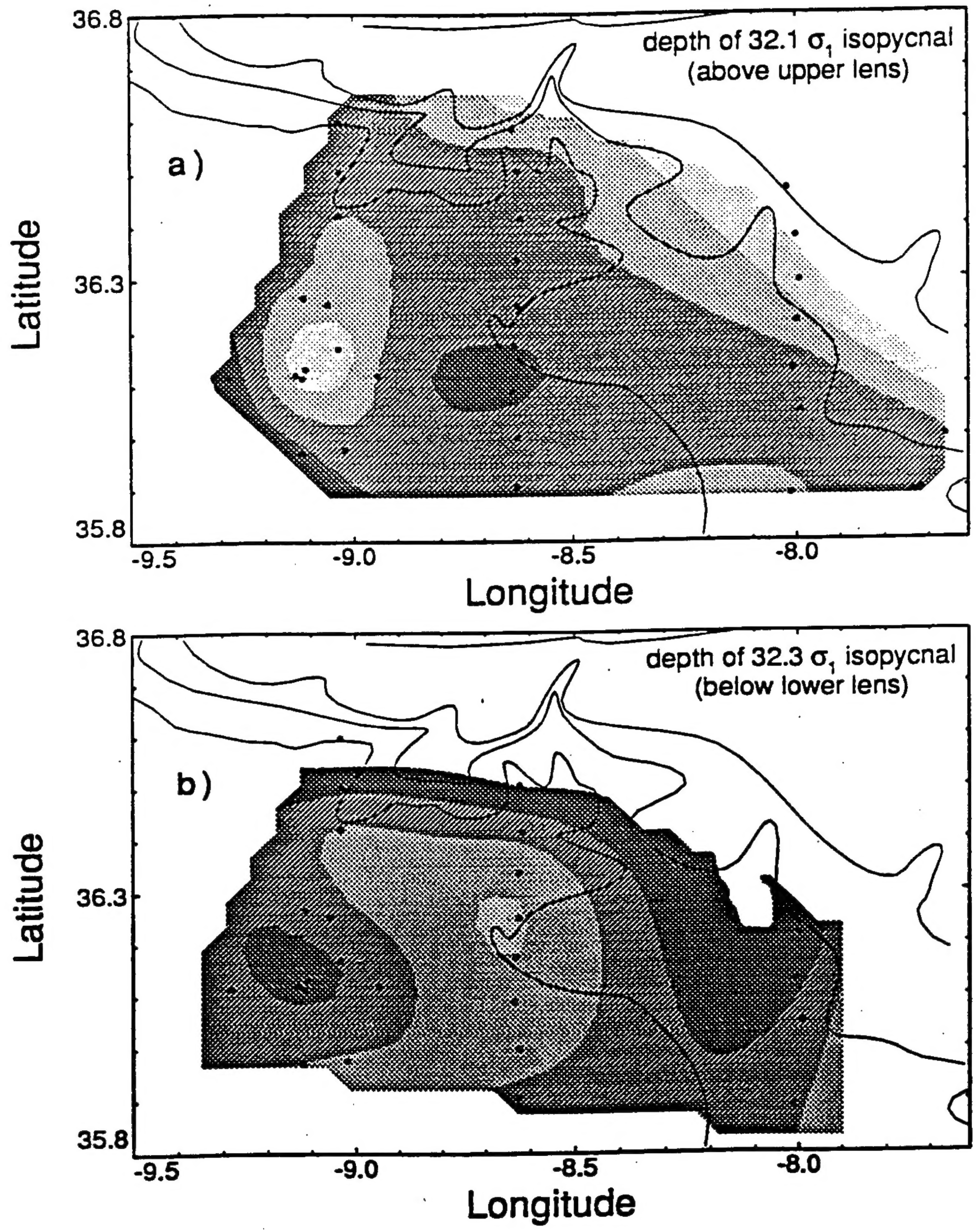
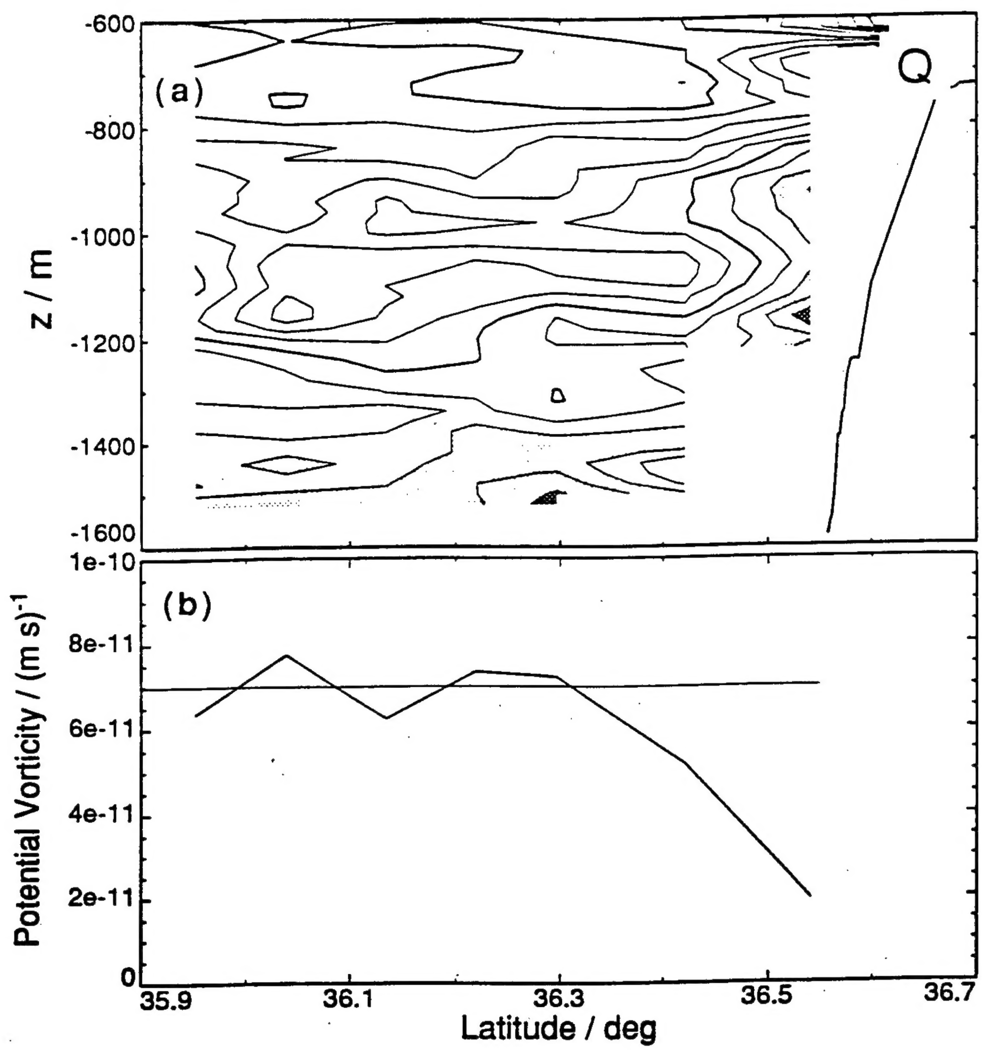


Figure 2: Contours of the depths of isopycnals in the Gulf of Cadiz. In both panels, the lightest gray shade is the shallowest, the darkest gray is the deepest. a) Depth of the isopycnal (32.1 σ_1) that had the maximum upward displacement above the Meddy. The range of contours is from 930 to 1030 dbars, with shading increments of 25 dbars. b) Depth of the isopycnal (32.3 σ_1) that had the maximum downward displacement below the Meddy. The range of contours is from 1290 to 1490 dbars, with shading increments of 50 dbars.



0 (m s)$^{-1}$ < ▩ < 1x10^{-11} (m s)$^{-1}$

1x10^{-11} (m s)$^{-1}$ < ▩ < 3x10^{-11} (m s)$^{-1}$

Figure 3: (a) Contours of Ertel's potential vorticity (Q) through a section near the Meddy formation south of Portugal. (b) Values of Q -930 m from panel (a). The values of Q in the outflow ($2 \times 10^{-11} (ms)^{-1}$) are similar to that found in the Cadiz Meddy.

He was a UCAR modeling postdoctoral fellow at the University of Rhode Island's Graduate School of Oceanography and is nwo on the research staff.

Med Outflow Studies

The Med outflow portion of the Expedition represents the most complete and synoptic study of this important source of this distinct water. The analysis was actively pursued at several institutions: UW, UVic, ULisbon and WHOI.

The main effort on this project has been investigations of the dynamics of the plume using the XCP, XDP and CTD data. This work was presented in an article in *Science* (Price *et al.*, 1993). The work with Greg Johnson and Rolf Lueck was an ambitious synthesis of three different types of data, and a detailed pair of papers were published in the *Journal of Physical Oceanography* . (Johnson *et al.*, 1994a; Johnson *et al.*, 1994b).

For the first paper we estimated bottom stress on the plume at various locations using the velocity profile method. We used changes in mass and volume transport to estimate turbulent buoyancy fluxes at the plume interface. >From the buoyancy fluxes we inferred the turbulent dissipation rates, and combined these estimates with the large-scale vertical shear at the interface to find the interfacial stress on the plume. The sum of the bottom and interfacial stresses are large, but compare very well in magnitude and distribution with bulk estimates of total stress on the plume calculated by Molly O. Baringer (A Ph.D. student with Jim Price at WHOI). This work was presented in January 1992 at the AGU Ocean Sciences Meeting in New Orleans, and in Spring 1992 in an oceanography seminar at the University of Washington.

For the second paper we estimated bottom stress on the plume using the turbulent dissipation estimates from the XDP data. The turbulent dissipation estimates were combined with large-scale shear from the XCP data to construct vertical profiles of stress in the plume. These stresses were found to be roughly three times smaller than those estimated using the XCP and CTD data in the work outlined above. Form drag, internal pressure gradients, geostrophic balance, buoyancy flux, and intermittency in the bottom boundary layer and at the interface are all possible mechanisms for creating this discrepancy between dissipation and velocity-profile stress estimates in the plume. This work was presented in January 1992 at the AGU Ocean Sciences Meeting in New Orleans.

Workshops

Meetings of expedition PIs, students and interested scientists have been held at Woods Hole (October 1989) and Seattle (April 1991). A final meeting was convened in Lisbon in fall 1991 under the hospitality of Dr. Isabel Ambar of the University of Lisbon. The proceedings of this workshop on the topic of Outflows and Overflows was published by the University of Lisbon (Ambar *et al.*, 1992). These meetings have been very helpful in stimulating collaborations and in encouraging participants to continue their analyses and comparisons.

Faroe Bank Channel Studies

A strong, steady outflow of cold, dense water from the Norwegian Sea enters the Atlantic Ocean through the Faroe Bank. Hydrographic sections across the channel reveal a wedge-shaped pycnocline, which is a common feature where water flows through long channels like the Vema Channel and the Samoa Passage. Our work focused on the role of friction and mixing in forming this wedge-shaped cross-stream density structure within the channel. We presented observational evidence for a strong cross-channel frictionally-driven secondary-circulation, and significant mixing at the interface between the outflow and the water above. We suggested that these cross-channel Ekman flows sharpen the density field on the left side of the channel looking downstream (in the northern hemisphere) and that the interfacial mixing spreads the pycnocline toward the other side of the channel.

This work was presented at various meetings including the AGU Ocean Sciences Meeting in New Orleans. It has been published in the *Journal of Physical Oceanography* (Johnson and Sanford, 1992).

The role of friction and mixing in the ocean was studied by Greg Johnson with Dan Ohlsen (an ONR-Funded Post-Doctoral Researcher working in Peter Rhines' new GFD Laboratory at the University of Washington). The frictionally modified rotating hydraulic channel exchange was studied using lab experiments and very simple analytical models. Greg and Dan showed that friction, rotation, and mixing can combine to generate a wedge-shaped interface in a channel flow that is very similar in shape to pycnoclines observed in the ocean channels mentioned above. They also made the first observations of which we are aware of interfacial Ekman layers in laminar two-layer rotating exchange flow. Perhaps most importantly, they showed, in the lab and with simple analytical models, that friction and rotation together act to limit hydraulic channel exchange more that either does separately. This is because frictionally-driven cross-channel circulation in a rotating system circulates spun-down fluid into the interior much more efficiently than the frictional boundary layers in a non-rotating system, greatly reducing exchange. This research was presented at seminars at the University of Washington, APS Meeting in Tallahasee, and 1992 AGU Fall Meeting in San Francisco. A paper was published in the *Journal of Physical Oceanography* (Johnson and Ohlsen, 1993).

Other Scientific Activities

Meetings, Conferences and Workshops

The PI served as an organizer of the ONR sponsored workshop on the MBL-ARI at Monterey in March 1992 and chaired the ocean sessions. This workshop presented the objectives of the ARI and resulted in statements of the ocean and atmosphere contributions.